DESIGN OF FRC FORMATION AND LINER COMPRESSION EXPERIMENT (F-LINCX) AT AFRL

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Abstract

An experiment to form, translate, and adiabatically compress plasmas in Field-Reversed Configurations (FRC's) is now being designed at the Air Force Research Laboratory in Albuquerque, NM. This experiment is referred to as "F-LINCX", for Formation, LINer Compression eXperiment. Over the past six years, the AFRL has been working in close collaboration with Los Alamos National Laboratory's FRC formation experiment, FRX-L. The AFRL experiment will reproduce the electrical properties of FRX-L to ensure that FRC's of similar parameters are formed. After formation, the FRC will be translated into the interior of a 10-cm diameter, 30-cm long aluminum solid liner, and the Shiva Star Capacitor Bank will be used to implode the liner and compress the FRC to magnetized target fusion (MTF) relevant densities and temperatures.

Based upon FRX-L's present configuration, the FRC formation will require four separate capacitor banks. These banks include two slow rise-time banks to first establish a bias magnetic field in a 10-cm diameter, 36-to-45-cm long theta discharge region and higher-intensity cusp fields at both ends of this region. Inside the theta discharge region will be a 50 to 100 mTorr deuterium pre-fill; a fast bank will pre-ionize this gas with an oscillating field comparable to the bias field. The last bank will drive a reverse-field in the theta discharge region with an amplitude approximately 10 times greater than the initial bias field. This bank will be crowbarred to lengthen decay time and FRC lifetime. To translate the FRC from the theta discharge region to the liner, one or two additional slow banks are needed to set up a guide field and a mirror field at the opposite end of the liner.

The status of the F-LINCX experiment is discussed, along with relevant circuit and hardware designs for the capacitor banks. A proposed design for the integrated theta discharge, translation, and liner implosion regions is also presented.

I. INTRODUCTION

The concept of the Field Reversed Configuration (FRC) has been in existence for more than forty years. It was discovered in the early days of theta pinch research when a main theta pinch magnetic field was applied in the opposite direction to an existing bias magnetic field in a plasma [1,2]. Since those early experiments, different laboratories throughout the United States, Europe, Russia, and Japan have undertaken a variety of studies related to the FRC, and tremendous improvements in the stability and lifetime of FRC's have been achieved as a result of these studies [3].

Much of the interest in FRC's in recent years has arisen due to their significant potential for use in a fusion reactor scheme. They have a simple geometry (Fig. 1) with a high β and a high power density, implying that a relatively efficient and compact reactor could be developed. Their magnetic field configuration includes a natural divertor, which will assist in reducing the amount of impurities entering from the vacuum vessel walls. They also have a demonstrated translatability, allowing the formation region and the region where subsequent heating occurs to be isolated from each other.

Over the past six years the Air Force Research Laboratory (AFRL) and Los Alamos National Laboratory (LANL) have been working together closely on separate

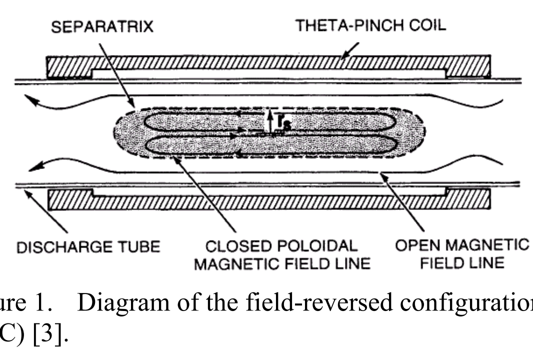

Figure 1. Diagram of the field-reversed configuration (FRC) [3].

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FRC formation and liner implosion experiments that together are intended to lead the way toward an eventual series of integrated fusion demonstration experiments. At LANL the FRX-L (Field Reversed eXperiment – Liner) plasma experiment has been established for studying the formation and translation of FRC's with parameters suitable for subsequent adiabatic liner compression to fusion-relevant temperatures and densities [4-6]. In parallel with this effort have been several implosion experiments with 30-cm long, 10-cm diameter aluminum liners at the AFRL's Shiva Star facility. These experiments have been performed to study the axial and radial uniformity of such imploding liners [7,8], with the most recent experiments having incorporated 8-cm diameter apertures into the liner electrodes [9]. Such apertures are needed to allow the FRC to be injected into the bore of the liner before the implosion.

Now, with the relatively broad knowledge base having been obtained from both series of experiments, attention is beginning to shift toward an integrated FRC formation, translation, and liner compression experiment intended for fusion demonstration. This paper outlines the efforts at the AFRL to link these two series of experiments, first duplicating the FRX-L experiment and then compressing an FRC with appropriate plasma parameters in an aluminum liner imploded by the Shiva Star Bank. The name F-LINCX, for Formation-LINer Compression eXperiment, is being used to describe this new experimental effort.

Section II first discusses the FRC formation process, the plasma parameters currently obtained with FRX-L, and the pulsed power requirements for the various formation steps. Section III then describes the scheme that is being developed at LANL to translate the FRC from the theta pinch region where it is formed into the bore of the aluminum liner. Requirements for the additional pulsed power systems needed for translation are also described. Lastly, Section IV presents a summary of the present status of the experiment assembly at AFRL.

II. FRC FORMATION AND PULSED POWER REQUIREMENTS

A. The FRC Formation Process

More detailed discussions of FRC features and the processes involved in their formation are given elsewhere [e.g., 4,5], but a short summary is included here for completeness. An FRC is a toroidal plasma configuration ideally having only a poloidal magnetic field. The poloidal field lines inside the toroid form closed loops, and an open field line region envelops the toroid. It is this open field line region that acts as a natural divertor (as mentioned in Section I), hindering impurities from entering the toroidal plasma and allowing any particles that are able to escape the toroid to do so along the axis rather than deposit their energy on the walls.

Figure 2 provides an illustrative description of the sequence of events in FRC formation with the FRX-L experiment [4] and soon with the F-LINCX experiment. First, Bias and Cusp fields are set up in the theta pinch region, and the background gas in the vacuum vessel is ionized with a high-frequency field generated by the Pre-Ionization bank. Next, the Main field, which is oriented opposite to the Bias field, is applied to compress the plasma. As the plasma is compressed, outer field lines from the Main field that have penetrated the plasma tear and then reconnect with field lines from the Bias field in the core of the plasma. The newly formed FRC continues to contract until equilibrium is reached. The initial pressure of the background gas, as well as the amplitudes and timings for each of the fields applied during formation, must be selected so that the equilibrium plasma density and temperature of the FRC reaches $\sim10^{17}$ cm^{-3} and 100-300 eV, respectively [6]. Densities and temperatures of this order are necessary to reach fusion-relevant conditions ($n \sim10^{19}$ cm^{-3}, $T \sim$ several keV) after liner compression.

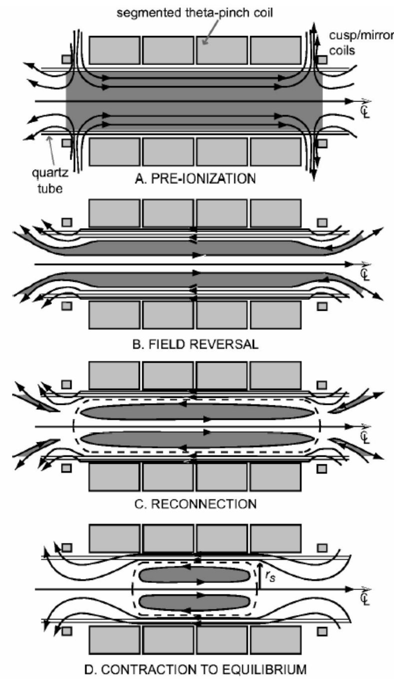

Figure 2. The FRC formation sequence: A. Bias and Cusp fields applied; background gas ionized. B. Main field applied. C. Field lines reconnect. D. Plasma contracts until equilibrium is reached [4].

B. F-LINCX Capacitor Banks

For the formation sequence just described, four separate capacitor banks are needed to generate the magnetic fields with appropriate amplitudes at the appropriate times, and three of these banks are required to drive the same set of Theta coils. Furthermore, one or two additional capacitor banks must be used for setting up Guide and Mirror fields to translate the FRC, as will be discussed in the next section. Figure 3 summarizes the electrical layout of all of these banks.

For the banks driving the Theta coils, care must be taken to isolate the lower-voltage banks (in this case the

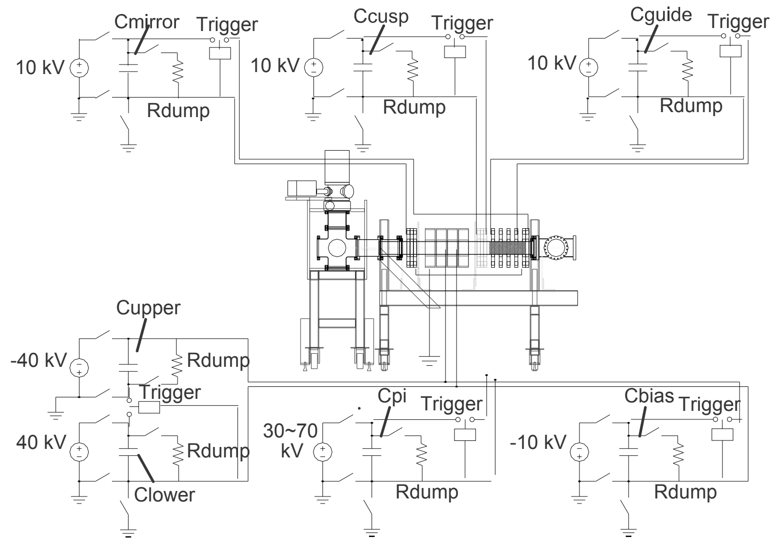

Figure 3. Circuit diagram of the F-LINCX FRC formation and translation banks (FRX-L vacuum vessel and field coils shown). C_{mirror}, C_{cusp}, C_{guide}, C_{pi}, and C_{bias} are the capacitances for the Mirror, Cusp, Guide, PI, and Bias banks, respectively. C_{upper} and C_{lower} are for the upper and lower halves of the Shiva bank module used as the Main bank. Connections for dump resistors (R_{dump}), power supplies, triggering units, and bank ground lifts are also indicated.

Bias bank) from the voltages impressed upon the coils by the higher-voltage banks (the PI and Main banks). This is accomplished by placing a large inductance (~2.2 μH) between the Bias bank and the theta coils. The grounds of all banks must also be lifted prior to triggering, as the single point experimental ground is located at the vacuum vessel for the benefit of the diagnostics.

Design parameters for each of the F-LINCX FRC formation banks are as follows. The Bias field bank will have a capacitance of ~2 mF and will be constructed from bank modules similar to those on FRX-L or from a partial AFRL "Slow Bank" module ($C_{slowbank}$ = 2.55 mF). The bank will be switched with ignitrons and will have a similar quarter-cycle rise time as on FRX-L (~140 μs).

The Pre-Ionization bank will generate an oscillating field at the same frequency as the FRX-L PI bank (~250 kHz). Because transmission line cables for the bank most likely will be longer than on FRX-L (and therefore have higher inductance), a smaller bank capacitance (2.1 μF) is being used to compensate. The bank charge voltage will also be increased to maintain the same PI field amplitude. A single rail-gap switch will switch the bank.

The F-LINCX Main bank will be similar to a Shiva bank module (C_{upper} = C_{lower} = 72 μF) except that the tall side of the capacitors will be placed horizontal to reduce bank height. Bank height is critical because, as will be seen in the last section, the Main (and PI) banks must be positioned under one of the Shiva bank arms when the Theta coils and vacuum vessel are positioned under the center of the Shiva bank. A quad set of rail-gap switches will switch the Main bank, and the quarter-cycle risetime will be similar to that of FRX-L (~2.6 μs) and have a peak field approximately 10 times that of the Bias field. Near the peak of the current pulse, the Main bank current will be crowbarred with a second quad set of rail-gap switches. The resulting longer decay time for the Main bank current pulse is needed to extend the FRC lifetime.

Unlike the other three banks, the Cusp bank is discharged into a separate set of field coils. Each Cusp coil is comprised of 16 turns of hollow copper conductor (square cross section) with a coil i.d. of 14 cm, and a coil thickness of 2.5 cm. One or more of these coils will be positioned on each side of the Theta coil to generate the Cusp field at the same time that the Bias field is generated. Exact parameters for the Cusp bank have not been determined at this time, but the bank will consist of one or two AFRL "Slow Bank" modules (maximum C of 2.55 mF each), each of which will be switched with ignitrons. The quarter-cycle rise time will be similar that on FRX-L (~900 μs).

III. TRANSLATION AND SUBSEQUENT COMPRESSION HEATING

Following formation, the FRC will be translated (vertically) from the bore of the Theta coils by approximately 80 cm into the bore of a 30-cm long, 10-cm diameter aluminum liner located at the center of the Shiva Star bank (Fig. 4). The wall thickness of the liner is nominally 1 mm, gradually expanding to 2 mm and then to 6 mm in two transitions when moving closer to the electrodes. As discussed previously, an 8-cm diameter aperture placed in the electrodes will allow the FRC to enter [9]. The time required to implode the liner is expected to be several μs longer than the time required to form and translate the FRC. As a result, current flow in the liner will actually be initiated before the FRC formation starts.

To help initiate the translation of the FRC from the Theta coil region, a modified theta coil design is currently being developed by our LANL team members [10]. In this design, the inner radius of each Theta coil segment is made slightly larger than the one below it, creating

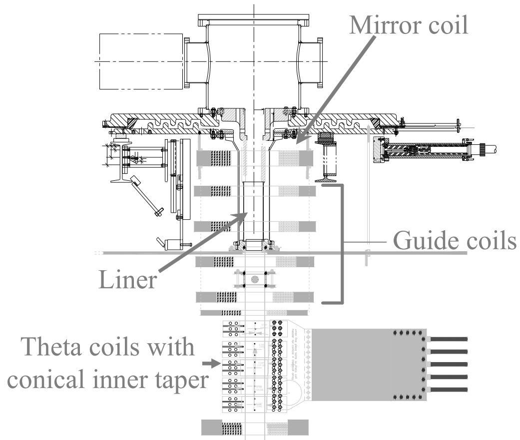

Figure 4. Arrangement of formation, translation, and mirror coils for F-LINCX under the Shiva Star bank.

somewhat of a conical profile with the wide opening of the cone directed toward the liner. Five coil segments are also used now instead of four, making the total coil length ~9.2 cm longer. The conical shape introduces a radial component to the theta coil magnetic fields; when the Main bank is triggered, not only is the plasma compressed and the FRC formed, but an axial momentum is introduced to begin translation.

Once the FRC exits the Theta coil, additional guiding magnetic fields will be required to transport the FRC to the liner. A Mirror field at the opposite end of the liner will also be needed to stop the translation of the FRC once it enters the liner. The parameters of the coils needed to generate such fields and their arrangement along the vacuum vessel and liner are also being analyzed at this time, so that the arrangement shown in Fig. 4 is somewhat conceptual at the moment. Depending upon current and voltage requirements for these coils, one or two of the AFRL "Slow Bank" modules will be used to drive them.

IV. PRESENT STATUS OF EXPERIMENT

At the time of this conference a majority of the pulsed power bank designs have been completed and a large portion of the hardware needed for the F-LINCX experiment are in house. Figure 5 shows the layout of the hardware around the Shiva Star bank. Slow banks, power supplies, and trigger units are being placed between B- and C-Arms of the Shiva bank. The fast banks (PI and Main) and vacuum vessel will be tested to the side of the Shiva bank and then moved underneath when preparing for FRC formation/compression tests. The reason for two test areas is that the outside area allows for greater personnel and diagnostic access to the hardware. Initial tests are intended to focus on diagnosing FRC plasma parameters and ensuring that all hardware is working correctly. Assembly of all of the F-LINCX hardware is targeted for completion by the end of this year, after which the FRC characterization tests will begin and data from these tests will be compared to that from FRX-L.

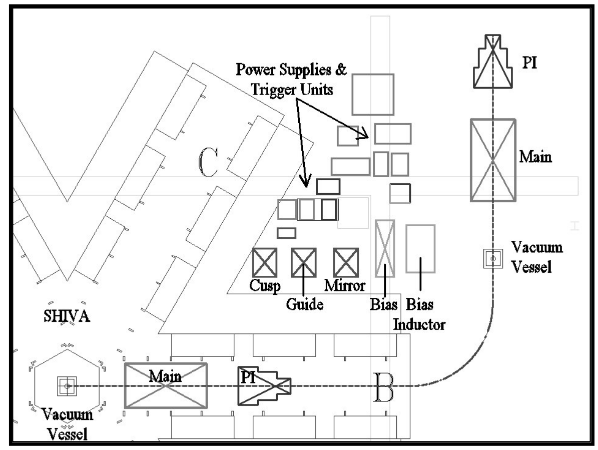

Figure 5. Tentative layout for the F-LINCX banks, power supplies and trigger units around the Shiva bank.

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